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13. ABSTRACT (Maximum 200 words)

The general goal of this project is to contribute to the development of advanced hybrid yarns for woven fabric body armor and general dynamic applications. Blending stiff low elongation-to-break (LE) fibers with compliant high elongation-to-brake (HE) fibers improves the overall strength of a blended yarn. Interfacial slip between fibers is thought to play an important role in this process. The specific objective of this work is to perform experiments on fiber-to-fiber interfacial slip behavior in fibrous assemblies. Various hybrid yarns were simulated (experimentally) by helicaly wrapping HE fibers over a LE core fiber at different helix angles. The strength characteristics of these blended yarns were tested in tension. In particular a novel experimental procedure is developed to measure the slip of the core fiber after the first brake occurs. The tests are carried out to show the existence of multiple breaks. The strength of the hybrid yarns is compared with the strength of a single yarn.

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Experimental Investigation of Slip and Strength Characteristics of Hybrid Yarns

March 17, 2003

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1. Executive Summary

1.1 Research objectives

The general goal of this project is to contribute to the development of advanced hybrid yarns for woven fabric body armor and general dynamic applications. Blending stiff low elongation-to-break (LE) fibers with compliant high elongation-to-brake (HE) fibers improves the overall strength of a blended yarn. Interfacial slip between fibers is thought to play an important role in this process. The specific objective of this work is to perform experiments on fiber-to-fiber interfacial slip behavior in fibrous assemblies.

1.2 Approach

Various hybrid yarns were simulated (experimentally) by helicaly wrapping HE fibers over a LE core fiber at different helix angles. The strength characteristics of these blended yarns were tested in tension. In particular a novel experimental procedure is developed to measure the slip of the core fiber after the first brake occurs. The tests are carried out to show the existence of multiple breaks. The strength of the hybrid yarns is compared with the strength of a single yarn.

1.3 Significance – Army value

It is clear from the present and ongoing research that improvement of strength and damage resistance characteristics of hybrid yarns will contribute to the development of stronger and lighter body armors and flexible deployable structures.

1.4 Accomplishments

In this work experiments were devised to investigate interfacial behavior in hybrid yarns, through the direct assembly of fibers in a blended structure. The hybrid yarns were subjected to tensile tests using an Instron machine. Different blended structures were considered. This work was carried out in collaboration with Dr. Thomas Godfrey of US Army Natick Soldier Center, Natick, MA. The experimental fixture was designed by Mr. John Jagodnik, who is a graduate student in the department, who also carried out the tests.

In order to measure the slip extent of the core yarn after the break, an original experimental procedure was introduced;

- Fifty equally spaced extension threads were glued perpendicular to the low elongation (LE) core yarn (Figure 1).
- A blended yarn was prepared by wrapping two high elongation (HE) outer yarns around the core in a helical manner (Figure 1).
- The blended yarn/extension threads assembly was placed in the Instron machine (Figure 3).
- Light tension was applied on the extension cords to keep them perpendicular to the blended yarn (Figure 2).
- Digital photographs were taken before load is applied to the blended yarn, to identify the initial angles of the extension threads.
- Axial load was, then, applied to the blended yarn and pictures were taken at set tension intervals, until core failure occurs.

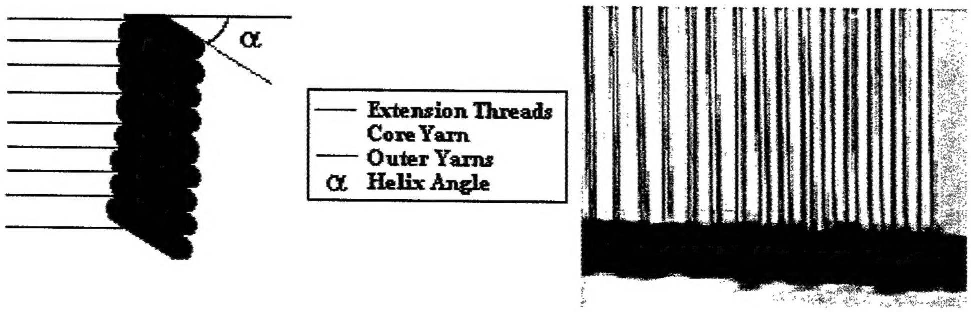


Figure 1. Schematic representing the extension threads, the outer yarn and the helix angle and an actual test sample.

- The slip at each point was calculated by comparing the initial and final angles of the extension threads, as depicted in Figure 2.

In this method the tensile properties of the core yarn are modified by the glue used to attach the extension threads. Tensile tests have been performed on the glued and unglued core yarns in order to determine the effect of the glue. Figure 4 shows that the glue on the core yarn a) increases its stiffness, and b) causes the strands of the core yarn to break simultaneously.

A comparison of the load-displacement curves, up to the first core break (extension = 0.16-0.28 in range), for the core yarn and the two blended yarns, in Figure 5, shows that the slope (stiffness) of the curve for the core yarn is non-linear and initially higher than those of the blended yarns. In contrast, the load displacement curves of the blended yarns are linear in this range. The outside yarn, wrapped around the core with a helix angle, appears to lower the stiffness of the blended yarn with respect to the core yarn. This curve also suggests that the stiffness of the blended yarn becomes lower with increasing helix angle.

Despite their apparent lower stiffness, the two blended yarns can withstand considerably longer elongations than the core yarn, which fails catastrophically at extension value of 0.16 in. Figures 6a and 6b show the load-displacement curves of the two blended yarns with $\alpha = 49^{\circ}$ and $\alpha = 57^{\circ}$, respectively. The presence of multiple breaks, is thought to be the evidence of slip assisted stiffening of the blended yarn.

The slip of the core yarn after the first break has been measured with the new technique. Figure 7 shows the slip as a function of the distance from the broken edge, for the two types of blended yarns. It can be seen that the slip is largest near the break and diminishes nearly linearly with distance away from the broken edge. This figure also shows that, in general more slip occurs at lower helix angle.

The experiments carried out in this work constitute a good first step to fill in the gap between the theoretical predictions [1,2] and the actual performance. More experiments are necessary to quantify the effects of the helix angle, and the blended yarn compositions.

The report begins by describing the procedure for creating blended yarns with extension threads in Section 2. The fixture and procedure for testing the blended yarn is explained in detail in Section 3. The computations that must be performed to determine the slip amounts from the digital images and information gathered during the testing stage are discussed in Section 4. Results from the initial test are presented and discussed

in Section 5, in order to establish that current test method is capable of determining the details of blended yarn slip. Improvements to the test method and objectives for future testing are discussed in Section 6. Recommendations and conclusions are also presented in this section.

1.5 Summary and Conclusions

A test procedure and test setup for measuring the amount of core yarn slip in a blended yarn is developed. Construction of the fixture and the measurement methods for testing the blended yarns have been described. The calculations for determining the slip amount were discussed and the results for the initial tests were discussed. These results suggest that this technique is capable of measuring slip, after the first break occurs in the core. It has been seen that a) the slip is largest near the break and diminishes nearly linearly with distance away from the broken edge; b) in general, more slip occurs at lower helix angle.

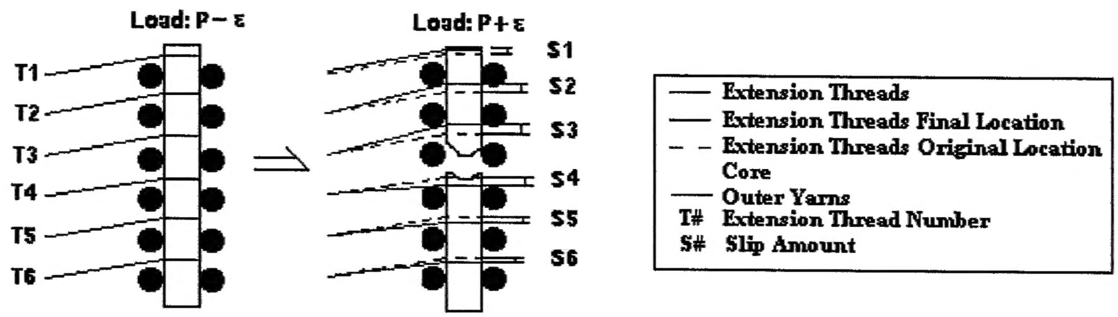


Figure 2. The schematic of slip measurements: Digital pictures are taken before and after the break occurs, and slip, S#, is calculated at each extension thread as shown.

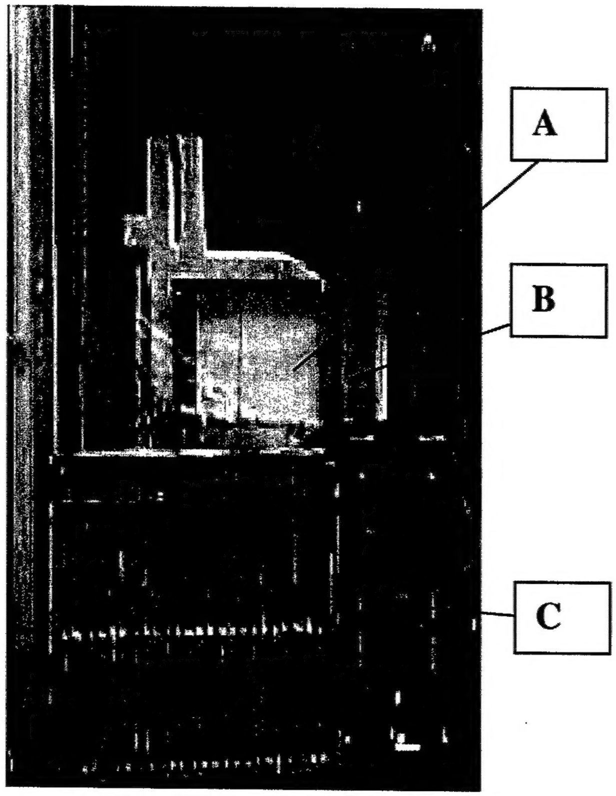


Figure 3. Depicting the extension threads (A), the test sample (B) and the method of keeping the xtension threads taught by using light weights (C)

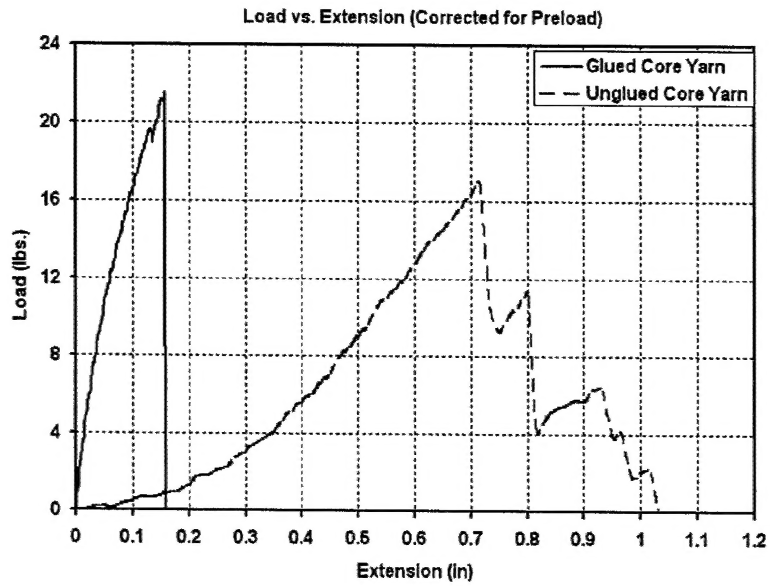


Figure 4 Load-displacement curve for glued & unglued core yarn

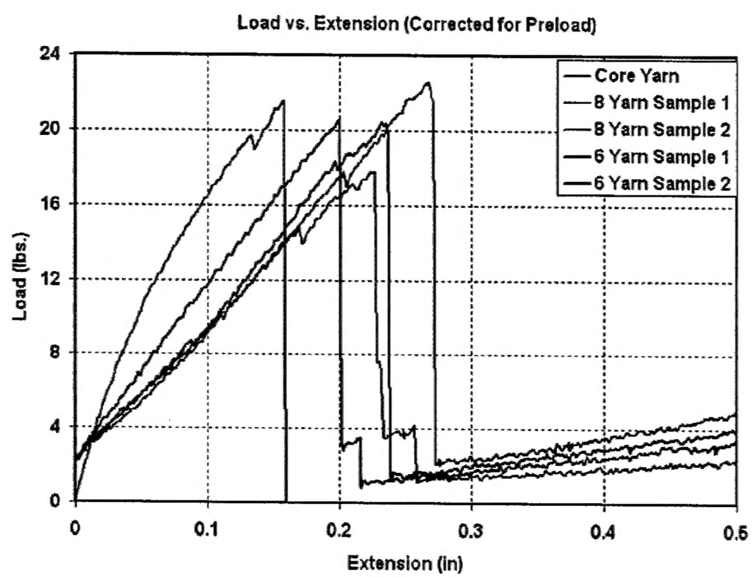
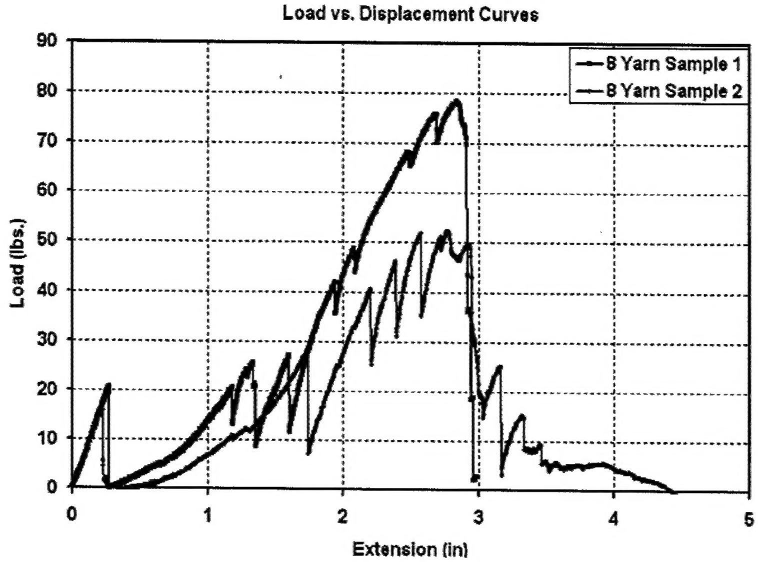
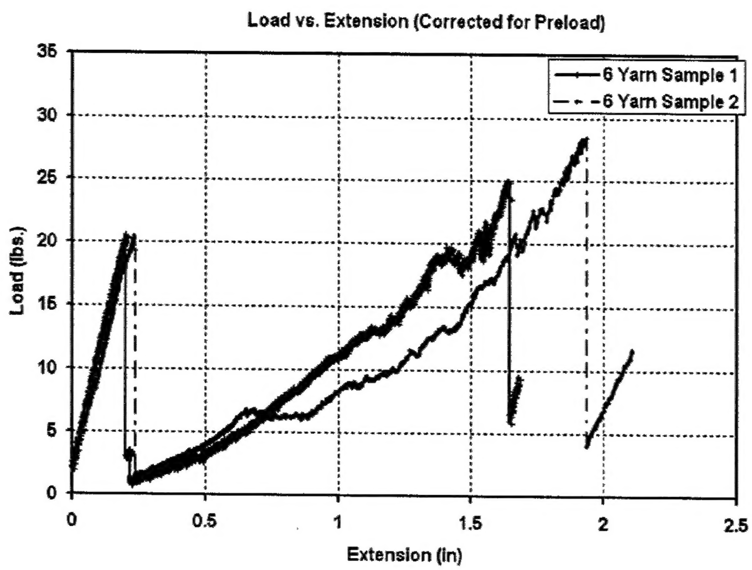


Figure 5 Load-displacement curve for core yarn, and $\alpha = 49^0$ (6 Yarn), $\alpha = 57^0$ (8 Yarn)

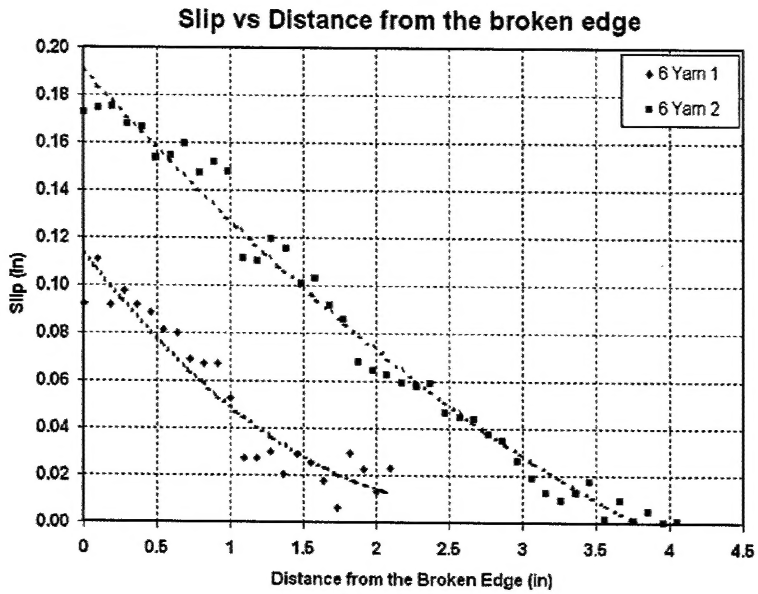


a) Helix angle, $\alpha = 57^0$

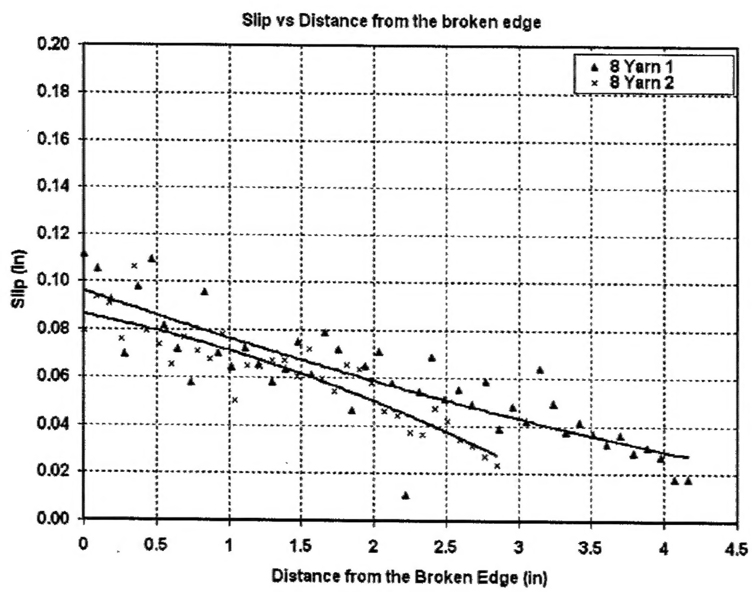


b) Helix angle, $\alpha = 49^0$

Figure 6 Load-displacement curve for helix angles, a) $\alpha = 57^\circ$ and b) $\alpha = 49^\circ$



a) Helix angle, $\alpha = 49^0$



b) Helix angle, $\alpha = 57^0$

Figure 7 Slip measurements as a function of the distance from the broken edge of the core for two different helix angles.

2. Preparation of the Blended Yarn Samples

In this report we introduce an Instron based test method for determining the slip within a blended yarn. A brief summary of the test procedures and initial results are presented below. These topics are discussed in great detail in the remainder of the report.

Blended yarn test samples are produced in a two-step procedure. 50 equally spaced extension threads are glued perpendicular to a low elongation core yarn to create the core shown in Figure 1b. Two high elongation outer yarns are wrapped around the core with a helix angle to create the blended yarn test sample shown in Figure 1a. A small imperfection is introduced at the center of the core yarn, to dictate the failure location. The blended yarn is then placed in the Instron machine and the extension threads are attached to a special fixture, which provides a small tension on each of the extension threads. Digital photographs are taken before tension is applied to the blended yarn, to identify the initial angles of the extension threads. Tension is then applied to the blended yarn and pictures are taken at set tension intervals, until core failure has occurred. The slip at each point can be calculated by comparing the initial and final extension thread angles.

The blended yarn test samples are composed of three parts; a low elongation core yarn; two high elongation outer yarns; and, 50 extension threads. Using a special fixture, the core is made by gluing 50 equally spaced extension threads perpendicular to the low elongation core yarn (Figure 8). The glue is uniformly applied to the top of the low elongation yarn and pressure is applied to the extension threads to create a firm glue interface.

Core yarn: The low elongation yarn is composed of 12 strands, which are 100% Egyptisk Makkabumull. Prior to gluing, two of the strands of the core yarn are cut near the center of the yarn. This forces the core to break near the center rather than at the stress concentrations near the Instron jaws. These strands absorb the Krazy Glue, creating a solid core fiber, which is significantly stiffer than the core yarn without the glue.

Extension threads: The extension threads are upholstery threads, which have significantly smaller diameters than the core yarn. The centers of the extension threads are spaced approximately 0.096 inches from each other, as shown in Figure 8. The extensions threads are then trimmed off on one side of the core yarn to create the core shown in Figure 8. The core is now ready to be wrapped with the outer yarn.

Outer yarns: The outer yarn is composed of 4 strands of a high elongation fiber. These fibers are one hundred percent acrylic. The outer yarns are helically wrapped around the core, so that the extension threads fall between the yarns (see Figure 9). During this wrapping process the helix angle is determined by skipping a number of extension threads. For example if two extension threads are skipped the constant helix angle becomes approximately 25°. After the outer yarn has been wrapper around the core, the outer fibers are glued to the core sufficiently far from the first and last extension threads. The glued areas prevent the outer yarns from unwinding before the sample is locked into the jaws of the Instron machine. These glued regions will be well within the Instron jaws, and thus will not effect the slip properties of the blended yarn.

Table 1: Properties of various yarns

	Unglued core yarn	Glued core yarn	Outer yarn
Maximum Strain (in/in)	0.11	0.05	0.44
Maximum Stress (psi)	7300	8200	1350
Young's modulus, E (psi)	153,549	174,300	6,474
Diameter (in)	0.054	0.054	0.11
Thread Weight (km/kg)	2.16	-	1.25

Figure 8a: Untrimmed and Glued Core Yarn (Digitally Enhanced)

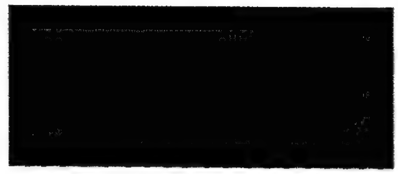


Figure 8b: Trimmed and Glued Core Yarn (Digitally Enhanced

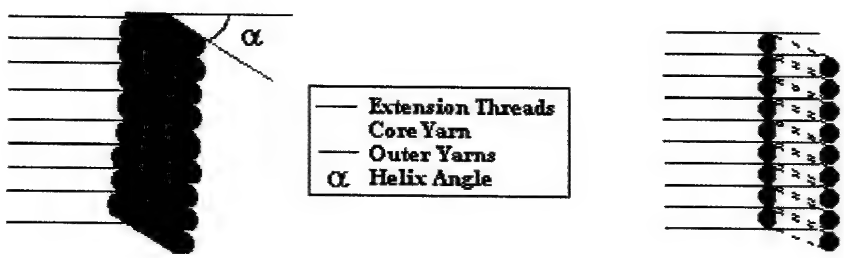


Figure 9 a) Blended yarn internal cut away with extension threads; b) View of the blended yarn.

2.1 Mechanical Properties of the Yarns

The Young's modulus of the core yarn and the outer yarns were measured with by tensile testing. Figure 4 shows a typical tensile test for the glued and unglued core yarns. Table 1 gives the properties measured for glued and unglued core yarns and the outer yarns.

Unglued core yarn: There are two interesting features to the stress strain curve given in Figure 4 for the unglued core yarn. First, there is a clear non-linear relationship at the beginning of the tensile test. This non-linear trend is assumed to be the result of slack removal in the 12 strands of the yarn. The second feature occurs in the break region. Several strands break at the peak stress value (at a strain of .075 in/in in Figure 3). The remaining strands are now able to move into the voids that were previously occupied by

the broken strands. This allows for additional strain to occur with a reduced load. The remaining strands then re-tension (at a strain of .080 in/in in Figure 3) and the stress increases slightly until additional stands rupture (at a strain of .085 in/in in Figure 3). This process continues until every strand in the yarn has ruptured.

Glued core yarn: The stress strain curve of the glued core yarn given in Figure 4 shows that the yarn becomes stiffer as a result of gluing. The entire yarn fails abruptly at a strain value of ~ 0.17, in contrast to the unglued yarn.

3. The Fixture

3.1 Design and Function

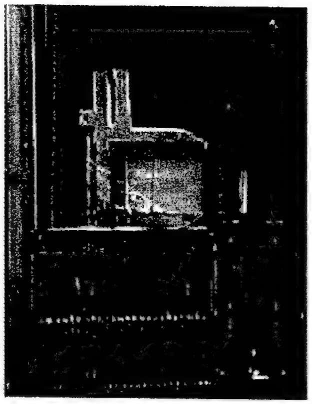
The wooden fixture displayed in Figure 10 was designed for use on the Instron machine to aid in detection of slip when blended yarn exceed the ultimate strain of the core yarn. Its main function is to keep the fifty extension threads attached to the core yarn taught. Thus the (slip) displacement of the core can be translated into rotation of the line formed by the extension threads. The fixture is bolted to the base plate of the Instron machine to ensure that the fixture does not move or rotate during the experiment.

The fixture is designed to handle different yarns, with minimal inconvenience. To test more than one yarn with the same length and helix angle, the fixture can be reused without requiring any changes. The fixture is composed of primary and secondary strings which ensure ease of usage of different core samples.

Primary strings: Fifty 1/8 gram lead weights are attached to primary strings. The primary strings and weights fit vertically into grooves as shown in Figure 11. These grooves allow the primary strings and weights to move freely up and down, but prevent unwanted horizon movement. A plexiglass front is screwed on to the grooved board with felt strips at the edges to prevent the strings from falling out of the desired grooves. The strings terminate after they exit the grooved board, where they are tied to a lightweight snap swivel. This will allow for the grooved board assembly to be reused in different configurations.

Secondary strings: are attached to each of the fifty snap swivels. These strings wrap around a thin dowel to redirect the strings and then proceed through a channel of fiftyone nails (see Figure 12). These nails create 50 thin channels which allow for unrestricted horizontal movement and angular displacements, while preventing vertical string movements. These secondary strings terminate after they exit the nail channel, where they are each connected to a lightweight barrel swivel.

The fifty extension threads from the blended yarn sample are threaded through a second fiftyone nail channel on the right side of the fixture (see Figure 13). This nail channel is approximately 2 inches from and parallel to the center of the blended yarn. These extension yarns are then tied to the end of the barrel swivels to create a link between the extension threads, secondary strings and primary strings. Once these links have been made, the weights provide a light tension on each of the fifty independently linked



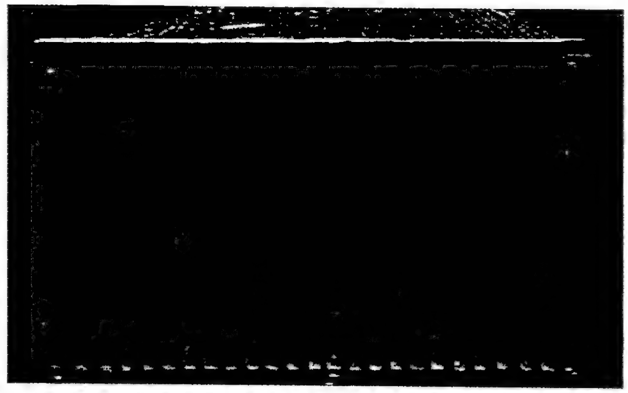
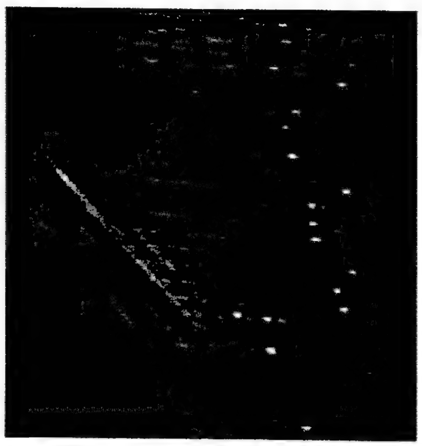


Figure 10: The fixture. Figure 11: Grooved slots and weights



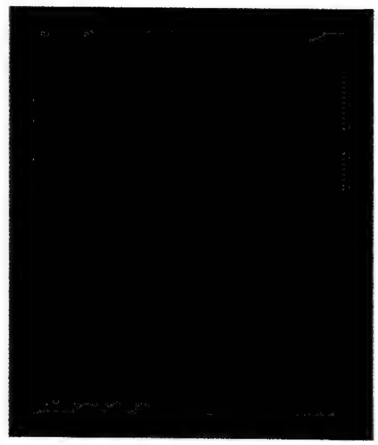


Figure 12: The first nail channel Figure 13: The second nail channel

strings. This removes any slack from the linked strings allowing for accurate measurements to be made. Cover plates, which are not shown in these figures, cover the two nail channels, preventing the linked strings from becoming dislodged from the nail channels.

3.2 Measurements

The fixture allows for two types of measurements to be made. The first measurement is the angle change in Region A (between the second nail channel and the blended yarn). In region A the angle of each extension thread can be recorded using digital photography. Figure 14 displays a "negative art" image of the first 10 extension threads. This image provides a clear and measurable picture of the extension threads.

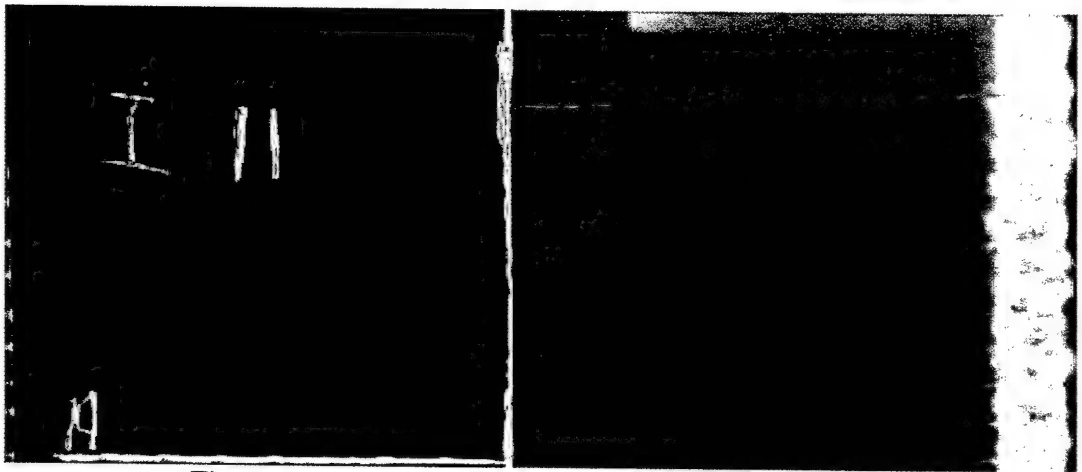


Figure 14: Negative art image of the extension thread angles

These types of pictures are taken before loading occurs and at several different load/extension levels. Using the initial angles as a benchmark, the displacement of each interior point of the core can be computed using the extension thread angles. This type of measurement is sufficient if small slip occurs. Figures 15a and 15b illustrate this concept. Figure 15 shows a cross section of the blended yarn at a load of P-ε, where P is the ultimate load which will cause core failure inside the blended yarn. Figure 15 shows the same yarn after core failure, at a load of P+ε. The important thing to note from this figure is that the slip amounts (S#) are small. Due to these small slip amounts, the soft outer yarns do not significantly resist the motion of the extension threads. The extension threads remain straight and the change in angle of each extension thread is sufficient to capture the slip amounts.

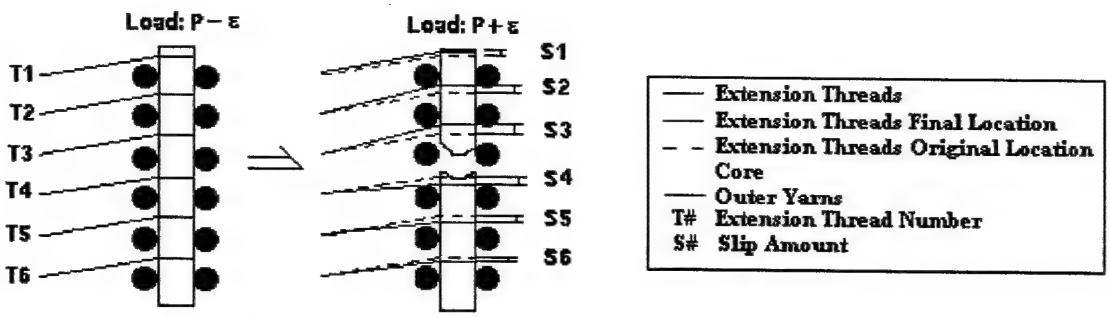


Figure 15a: Blended yarn before core failure

Figure 15b: Blended yarn after core failure, with small slip amounts

If large slip amounts occur, a second measurement must be made. Figures 16a and 16b display the same slip configuration when large slip amounts occur. In this figure, the slip amounts are large, causing the extension threads to compress the outer yarns until the outer yarns are able to resist the motion of the extension threads. The extension threads then rotate around the outer yarns and move vertically parallel to the core. Simply measuring the change in angle will not be able to capture the true slip amounts in this case. In order to measure these large slip amounts, the angle change of each extension thread and the horizontal displacements between the two nail channels must be recorded.

Using these two measurements, the slip amounts can be found for each extension thread. The horizontal displacements of the extension threads between the two nail channels can also be recorded and measured using digital photography, referencing the initial unloaded thread positions.

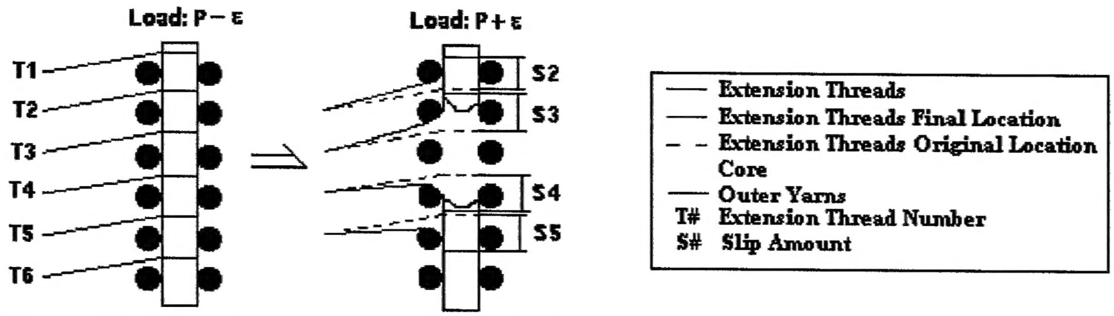


Figure 16a: Blended yarn before core failure

Figure 16b: Blended yarn after core failure, with large slip amounts.

4. Experiment

4.1 Blended Yarn Testing

The blended yarn is attached to the Instron using the same cross hatched flat grips on both sides. The extension threads are then attached to the fixture as discussed in the previous section. The extension thread were separated into 5 groups, to allow for higher zoom levels in the digital photography. Initially, 5 pictures were taken before any loading was introduced (Image Set 1). The blended yarn was then loaded and paused at different strains to take new pictures.

4.2 Computing Total Displacements and Slip for Core Points

In addition to the angles measured from these images, the distance from the second nail channel to the center of the core must be measured. Figure 17 displays a digital image of the blended yarn before testing, with the cover plate removed from the second nail channel.

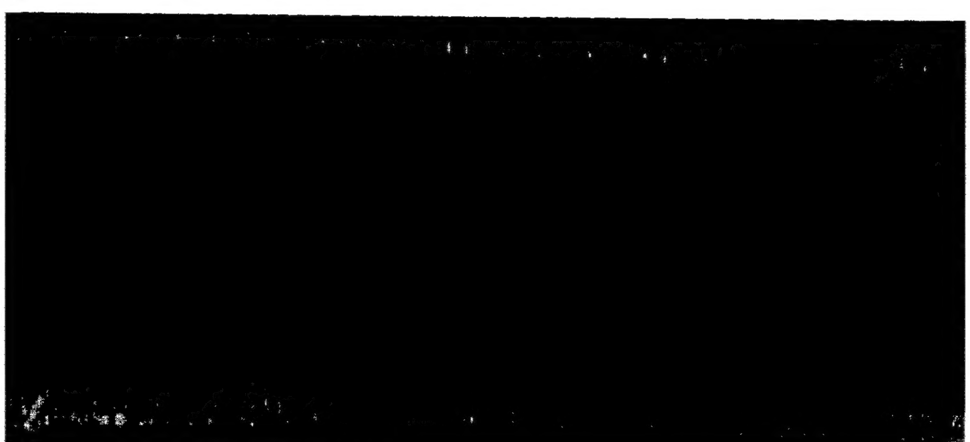


Figure 17: Digital image for the perpendicular length measurements

This image was imported into AutoCAD and points were drawn at the center of each channel created by the nails. These points were connected with a line to the centerline of the blended yarn. These 49 lines were subjected to a perpendicular constraint, with respect to the blended yarn centerline. The lengths of each line as well as the length of the blended yarn (from jaw to jaw) were measured. The measured length of the blended yarn is then divided by the known true length (L_{yarn}) of the blended yarn (5.76 in) to obtain the zoom factor (3.17). Each length measurement is then divided by the zoom factor to obtain the perpendicular lengths of the extension threads ($\bar{L}_i$), as shown in Figure 18.

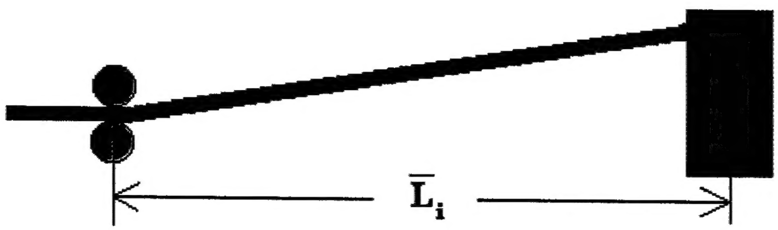


Figure 18: Perpendicular extension tlread Lengths

Figure 18 also demonstrates that the length from the center of the core yarn to the pivot point of the extension yarn is not the length we are interested in. The extension yarn is glued across the entire surface of the core yarn, and therefore is unable to bend in this region. With this understood, we are interested in the distance from the edge of the core yarn to the pivot point of the extension yarn. The true extension yarn length (L_i) is now computed by subtracting out the radius of the core yarn (R_{core}):

$$L_i = \bar{L}_i - R_{core}$$

The displacements of the 49 points on the core yarn can now be found geometrically. Focusing on Figure 19, where the purple line and red line are the initial (image 1) and final (image 7) locations of extension thread i, the displacement of point i (D_i) is found as:

$$D_i = L_i\left(\tan\left(\theta 7_i\right) - \tan\left(\theta 1_i\right)\right)$$

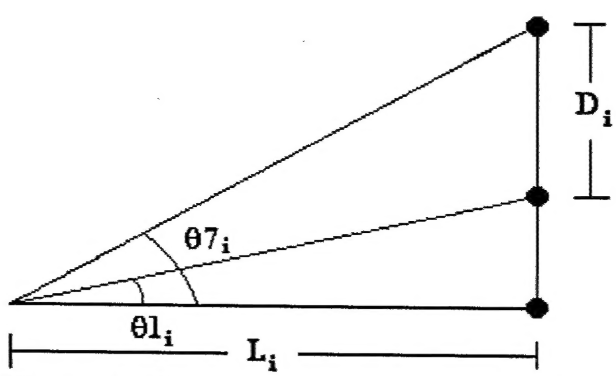


Figure 19: Geometry of the extension threads

After calculating the displacements of all 49 points, the expected displacements (E_i) must be found. The expected displacements are the displacements caused by the strain in the

blended yarn, if core failure had not occurred. Neglecting end effects, the expected displacements are linear, changing from 0 at the fixed lower jaw, to the total elongation (D_{yarn}) of 0.226 inches at the upper jaw. Assuming the core was produced perfectly, each extension thread would be spaced 0.0959 inches from its two neighboring extension threads. With the distance from the lower jaw to the first extension thread (H) measured at 0.3295 inches, the distance from the lower jaw to point i (V_i) is found as:

$$V_i = H + (0.0959)(49 - i)$$

where the points are number from 1 to 49 starting from the top of the blended yarn.

E_i is then found as the product of the total elongation and the length fraction of point i:

$$E_i = \frac{D_{yarn} V_i}{L_{yarn}}$$

The slip for point i (S_i) is then found as:

$$S_i = D_i + E_i$$

Here a downward slip is defined negative.

5. Recommendations

5.1 Future Works

Several improvements can be made to the experiment and fixture in order to improve the results. First and foremost, the winding and clamping of the blended yarn will be done with more care. For the above-mentioned sample, the extension threads were not in a straight vertical line on the Instron, but rather a slight helix. Figure 20a shows the ideal clamped configuration, where all the extension threads are aligned perfectly vertical with respect to each other. Figure 20b shows the actual configuration where the blended yarn has rotated slightly during clamping, causing a non-vertical alignment of the extension threads. This is evident in the sample as shown in Figure 20c.

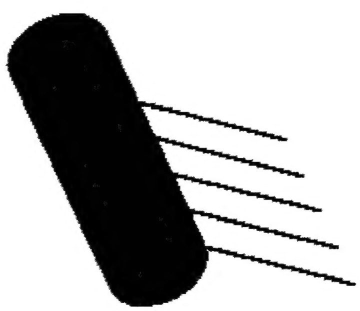


Figure 20a:Perfect sample clamping

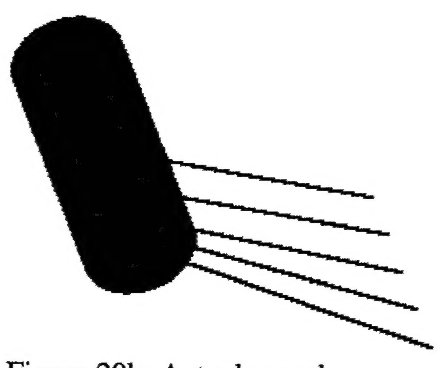


Figure 20b: Actual sample clamping

Figure 20c: The test sample

In addition to this clamping issue, other improvements can be made to increase the accuracy of the results. As previously mentioned, the outer yarns can be wrapped around the core under higher tension to create a slip free zone at each end of the yarn. The grips

can also be placed significantly closer to the first and last extension yarns to obtain information about how the slip approaches zero near the jaws.